Electrical Characterization of Thin films at the Nanoscale

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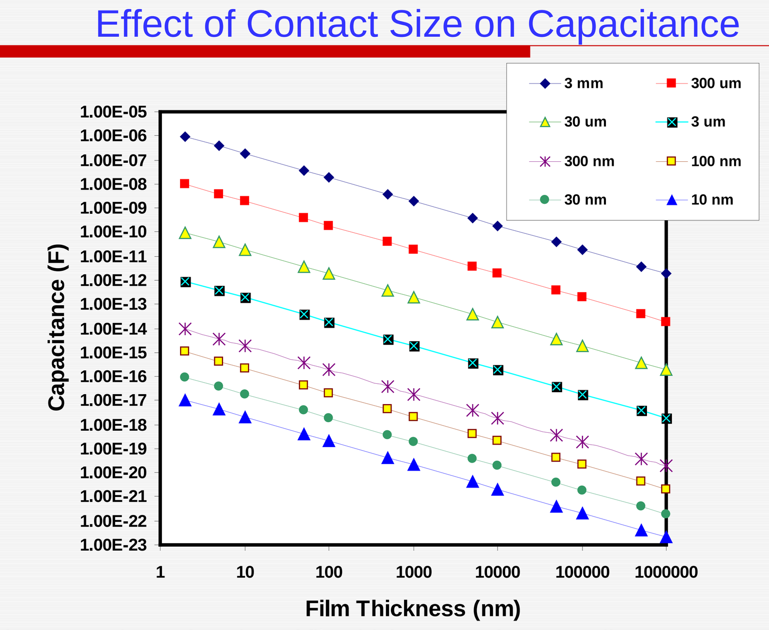
Introduction

- Nanotechnology has opened up many interesting research avenues to investigate. With the new exciting developments in carbon nanotubes, graphene and synthesis of a wide range of other nanomaterials and nanocomposites, the new challenges in terms of electrical property measurements have not yet been widely recognized. Often, measurements of these nano-objects and their devices are obtained by simply attaching contacts to them and reporting the measured values obtained.
- In this presentation, we demonstrate that one needs to be very careful when making measurements at the nanoscale, because there are many factors that can affect the measured response. For thin films they include:
  - Magnitude of the material properties such as resistivity and dielectric constant, film microstructure and orientation
  - Substrate properties and surrounding medium
  - Film thickness and size of contacts used to probe the properties
  - Shape and type of material used for electrical contacts, which will determine if contacts are ohmic or non-ohmic
  - Strength of the signal used to probe the material being tested
  - Signal type: ac, dc, V_{rms}, dc bias, 2-probe vs. 4-probe, etc.
  - Testing equipment specifications and set up parasitics

Procedure Used

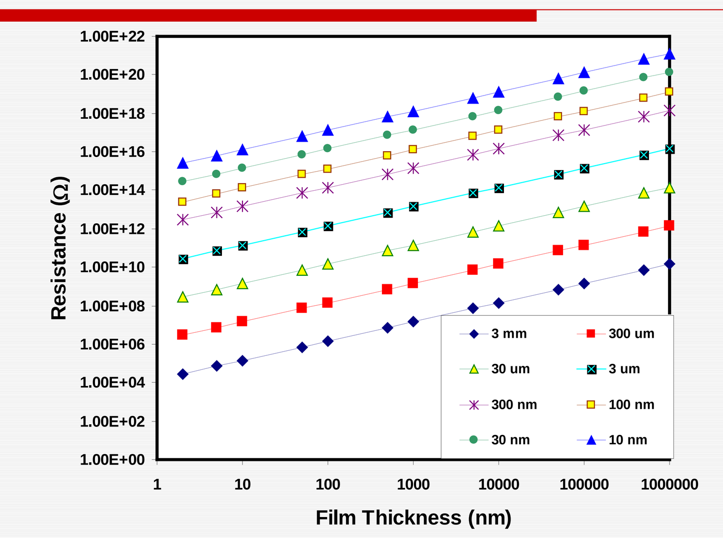
- Calculate expected R and C for thin films as a function of film thickness and circular contact area.
- Simulate the expected impedance spectra based on those circuit elements.
- Establish measurable limits based on equipment capabilities
- Numerically simulate the impedance response taking into account the properties of the surrounding medium.
- Compare numerical simulations to simple analytical models
- Compare calculated values with actual measured values of some ideal films.

Effect of Contact Size on Capacitance



- Shows trend as a function of film thickness and contact diameter.
- Film relative permittivity = 30, film conductivity = $1x10^{-8}$ S/m.

Effect of Contact Size on Resistance



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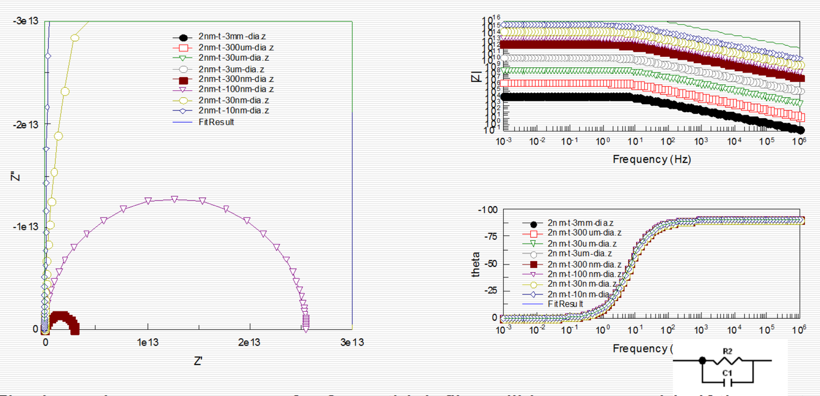
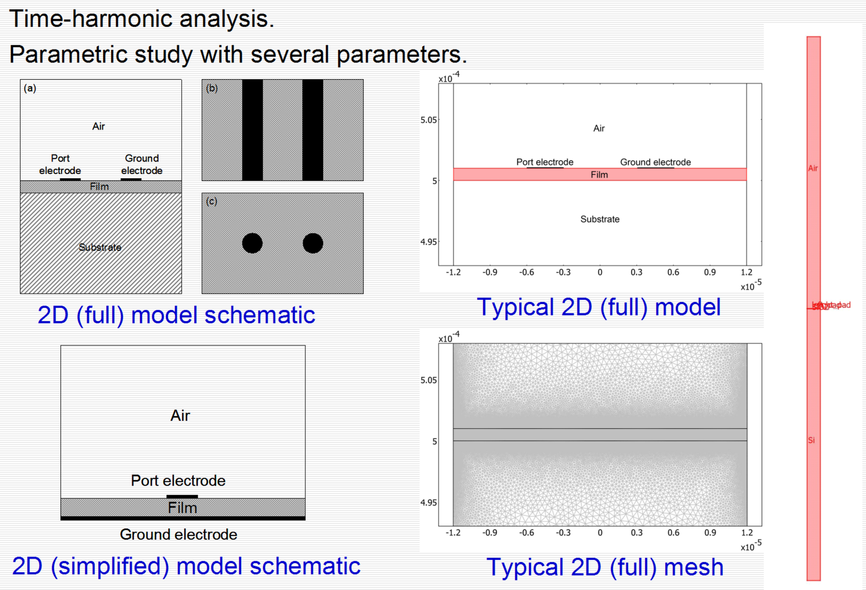
Calculated Impedance Response (2 nm Thick Film)



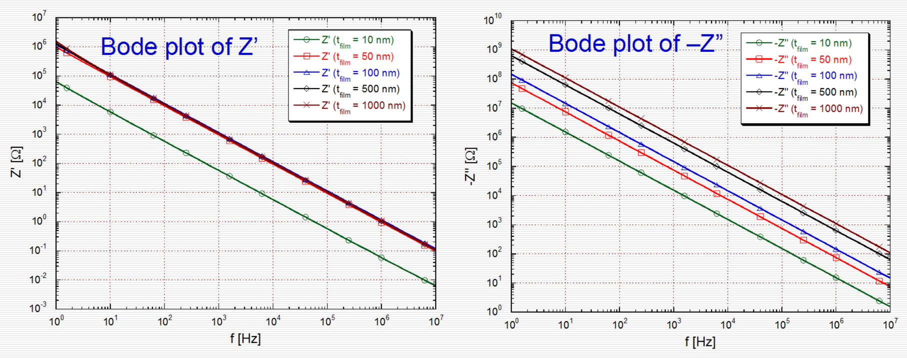
- The impedance response of a 2 nm thick film will be measurable if the contact area is sufficiently large.
- However, when using too small a contact diameter, the expected values of R and C will exceed most normal equipment specifications!
- No equipment can measure impedance greater than 10^{16} ohms.
- The advantage of using ac measurements is that one can usually get measurable data at the highest frequencies.

Impedance Simulation Using COMSOL

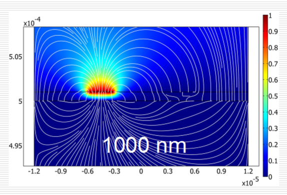
- COMSOL Multiphysics simulation for comparison with experimental results.
- Time-harmonic analysis.
- Parametric study with several parameters.



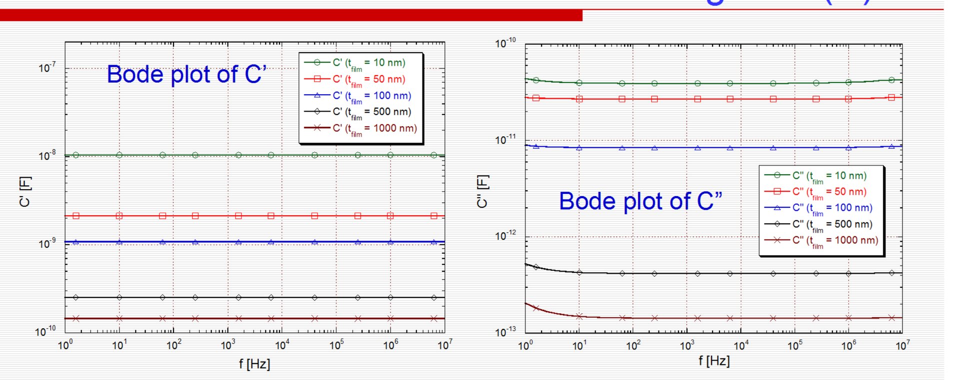
Effect of Film Thickness on Insulating Film (Z)



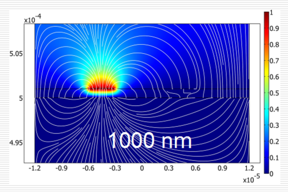
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 10 to 1000 nm, film conductivity = $1x10^{-13}$ S/m.
- Si thickness = 500 μm, Si conductivity = 100 S/m.
- Z' does not change much.
- -Z" shows increasing trend with film thickness.



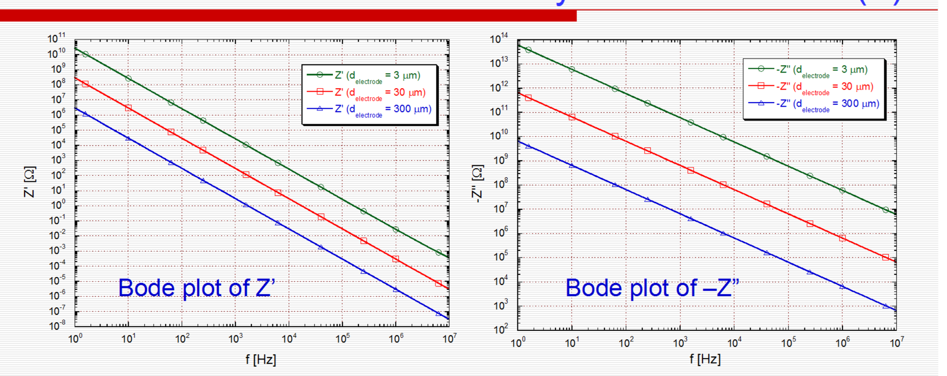
Effect of Film Thickness on Insulating Film (C)



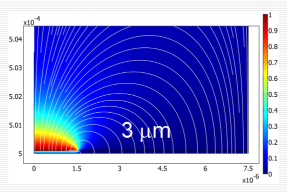
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 10 to 1000 nm, film conductivity = $1x10^{-13}$ S/m.
- Si thickness = 500 μm, Si conductivity = 100 S/m.
- C' shows decreasing trend with film thickness.
- C" also shows decreasing trend with film thickness, and curvatures are seen.



Effect of Electrode Size - Axisymmetric Models (Z)



- Pad diameters, 3 μm, 30 μm, 300 μm.
- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film conductivity = $1x10^{-13}$ S/m.
- Si thickness = 0 um (Bottom electrode present).
- Capacitance values almost the same as for simple parallel plate capacitor.



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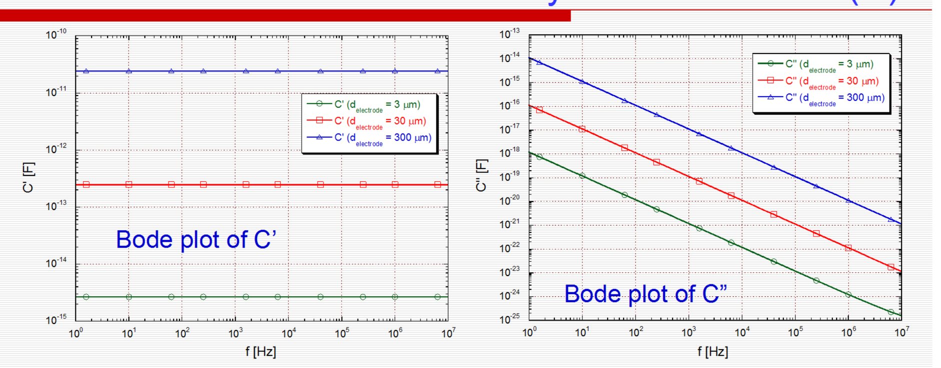

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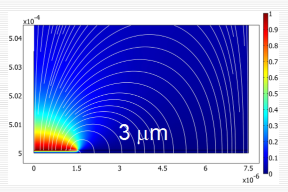
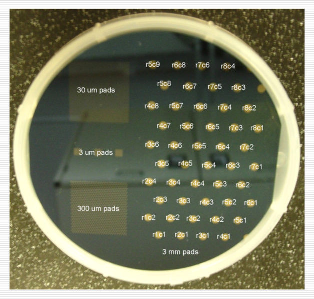


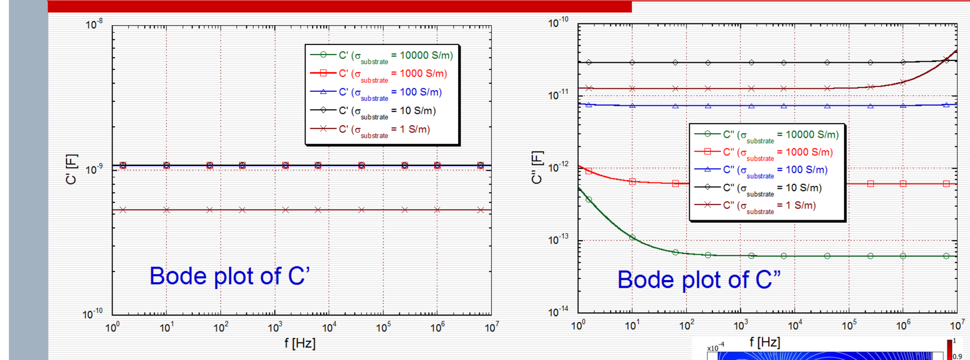
Comparison of Measurement/Calculation (SiO_2 Films)



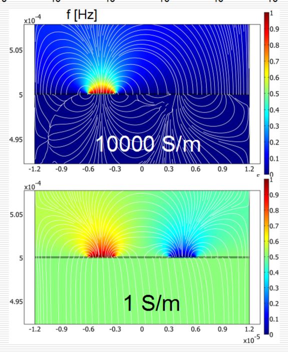
Diameter (μm)	Analytical (F)	Simulation (F)	Error (%)
3000	2.441×10^{-9}	NA	NA
300	2.441×10^{-11}	2.444×10^{-11}	0.14
30	2.441×10^{-13}	2.468×10^{-13}	1.10
3	2.441×10^{-15}	2.656×10^{-15}	8.82

- Pad diameters, 3 μm, 30 μm, 300 μm.
- Air thickness ~ 500 mm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film conductivity = $1x10^{-13}$ S/m.
- Si thickness = 0 mm (Bottom electrode present).
- For smaller electrodes the difference is higher due to edge effects.
- Measured values were:
  - For 300 μm pads: experimental ~ $2\times8.45\times10^{-12}$ F = 1.69×10^{-11} F
  - For 3 mm pads: experimental ~ $2\times1.17\times10^{-9}$ F = 2.34×10^{-9} F
  - For smaller pads: data will be reported elsewhere

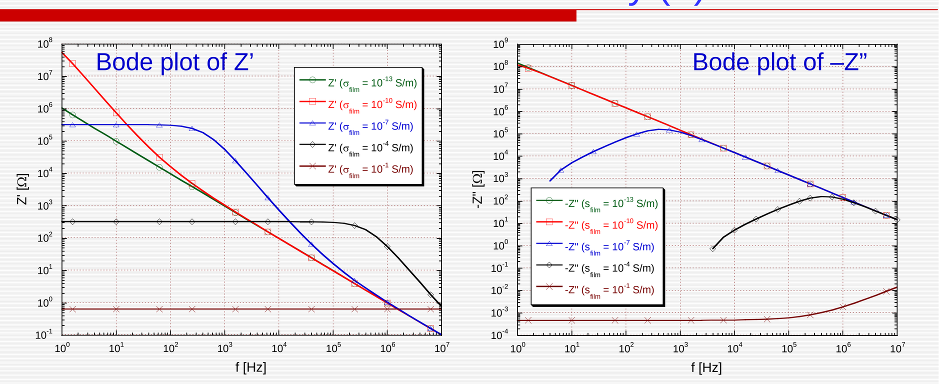
Effect of Substrate Conductivity (C)



- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film sigma = $1x10^{-13}$ S/m.
- Si thickness = 500 μm, Si conductivity = 1 to 10000 S/m.
- Imaginary part of C shows some change.
- Drastic difference in the potential profiles.

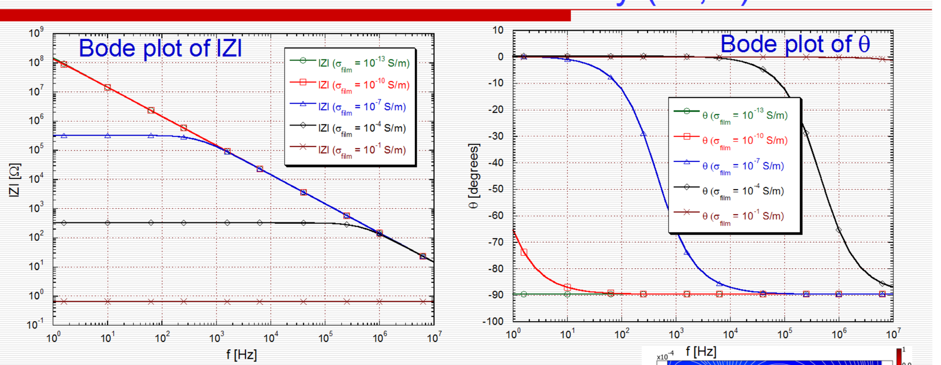


Effect of Film Conductivity (Z)



- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film sigma = $1x10^{-1}$ to $1x10^{-13}$ S/m.
- Si thickness = 500 μm, Si conductivity = 100 S/m.
- Shows decreasing plateau height with film conductivity.

Effect of Film Conductivity (|Z|, θ)



- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film sigma = $1x10^{-1}$ to $1x10^{-13}$ S/m.
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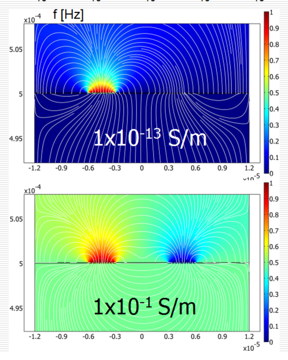
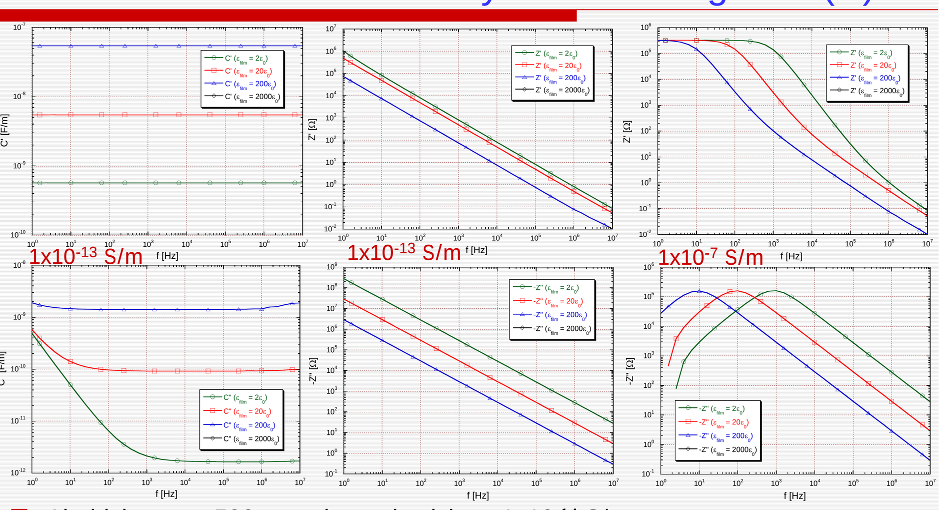


Effect of Film Permittivity on Insulating Film (C)



- Air thickness ~ 500 μm, air conductivity = $1x10^{-14}$ S/m.
- Film thickness = 100 nm, film sigma = $1x10^{-13}$ S/m and $1 x 10^{-7}$ S/m.
- Si thickness = 500 μm, Si substrate conductivity = 100 S/m.
- Film relative permittivity = 2, 20, 200, 2000 (?).
- Increasing conductivity has a noticeable effect on the resultant properties

Conclusions

- Numerical simulation using COMSOL was extremely useful in assessing the effect of film conductivity, substrate conductivity, dielectric properties of the film and other factors
- All simulations assumed ideal conditions. It was shown that when a film is insulating, it is possible to obtain reasonable results regardless of whether one uses a parallel plate arrangement or surface electrodes so long as the substrate conductivity is sufficiently high. When the substrate conductivity is more comparable to that of the film or object being measured, the contribution from it needs to be taken into account.
- It was also shown that when the film properties are more conducting or have larger dielectric constants, that it is easier to observe frequency dependence.
- It was also shown that for a given set of film properties, changing the film thickness and electrode contact area has significant effects on what values of R and C are able to be measured.
- Equivalent circuit modeling was demonstrated to be useful for helping determine if frequency dependence can help identify the existence of additional processes.
- All of the above results have implications on the accuracy of electrical measurements on nanosized objects and that one needs to pay attention to not only the expected properties of the material but also the surrounding medium, such as the conductivity and dielectric properties of the substrate, the surrounding atmosphere, the electrode contact size and the film thickness.
- There are many other experimental variables that can also have an effect on the resultant response during experimental measurements.

Acknowledgements

- Funding from the U.S. Department of Energy Basic Energy Sciences under contract DE-DE-FG02-03-ER46035
- Nickolay Lavrik of Oak Ridge National Laboratory (ORNL) for growing SiO_2 thin films on Si substrate and making the samples available for the experimental measurements.

References

- R.A. Gerhardt, "Impedance Spectroscopy" in *Encyclopedia of Condensed Matter Physics,* pp. 350 Elsevier Press (2005).

Nanotech 2009 -2009 NSTI Nanotechnology Conference and Expo Houston, May 3-7, 2009